FAMA-PJ: A Channel Access Protocol for Wireless LANs

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Abstract

We specify and analyze a new channel access protocol for wireless local area networks. The new protocol, FAMA-PJ, consists of both carrier sensing and a collision detection mechanism based on control packets and jamming that prevent collision of data packets with control or data packets from other stations. Control of the channel (which we call the floor) is assigned to at most one station in the network at a time, and this station is guaranteed to be able to transmit one or more data packets to different destinations with no collision with transmissions from other stations. The minimum control packet size required to enforce correct floor control is specified as a function of the channel propagation delay and transmit to receive turn around time. The throughput and delay of FAMA-PJ are analyzed and compared with the throughput and delay of non-persistent CSMA. This analysis shows that FAMA-PJ can provide similar or better throughput than non-persistent CSMA in a high-speed wireless local area network, and that is more stable and has better delay characteristics than non-persistent CSMA.

1 Introduction

Wireless local area networks (WLANs) are playing an increasingly important role in the future of personal communications. Devices such as the personal data assistant (PDA), the personal information communicator (PIC), and personal computers with radio modems are widely available. These devices are generally mobile and operate intermittently due to the power considerations of mobile operation.

In many WLANs, the communication medium the devices use is a single radio channel. Our research investigates the development of a medium access control (MAC) protocol for WLANs in which all stations are within hearing distance of one another.

Our protocol practices collision avoidance using carrier detection in a manner similar to Carrier Sense Multiple Access (CSMA) [10]. CSMA protocols use the sensing of the channel prior to a transmission to avoid colliding with other transmissions already in progress in the channel [10, 16]. The CSMA protocols can be further extended into two major subgroups: collision detection (CSMA/CD) [12] and collision avoidance (CSMA/CA) [5]. CSMA/CD is an efficient protocol and is used in Ethernet networks [12]. The transceiver listens during its own transmission and terminates the transmission upon detecting a collision with other signals in the channel. However, CSMA/CD cannot be applied directly to WLANs because the radios in these networks cannot listen to the channel during their own transmissions, making collision detection difficult. CSMA/CA is a variant of CSMA/CD. A sender to the channel transmits a short burst if the channel is clear , listens again, transmits another short burst with a short pause followed by the data packet. The destination station returns an ACK/NACK immediately after the end of the data packet for verification to the sending station.

The AppleTalk© Link Layer Access Protocol [15] is a proprietary protocol based on CSMA/CA intended for a wire based network. For wireless LANs another variant of CSMA/CA that does not use carrier sensing called Multiple Access with Collision Avoidance (MACA) has been suggested [8]. Because MACA does not use the carrier sense principle, it can be shown that MACA will allow collisions of the data packets and therefore is not safe [6]. An extension to MACA titled MACAW (MACA for Wireless) has also been proposed [1]. A version of CSMA with a four-way handshake for collision avoidance has been proposed for the IEEE 802.11 [3, 7]. In all these protocols, data packets may collide with other packets.

We present a new channel access protocol that we call floor acquisition multiple access with pauses and jamming (FAMA-PJ). The objective of FAMA-PJ is to allow a station that has data to send to acquire control of the channel (which we call the floor) before sending any data packets, and to ensure that no data packet can collide with any other packet. In contrast to prior collision avoidance MAC protocols that assign the channel dynamically (e.g., SRAM [17], BRAM [4], MSAP [9]), FAMA-PJ does not use control subchannels or preambles. Section 2 describes the operation of the FAMA-PJ protocol. Section 3 shows that the FAMA-PJ protocol assigns the floor correctly, i.e., at most one station can send data packets at any given time. Sections 4 and 5 analyze the the throughput and delay of the protocol and compare it against non-persistent CSMA. Section 6 presents our conclusions.

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2 FAMA-PJ

FAMA-PJ requires a station who wishes to send one or more packets to acquire the floor before transmitting the packet train. The floor is acquired using control packets that are multiplexed together with the data packets in the same channel in such a way that, although control packets may collide with others, data packets are always sent free of collisions. There are different schemes with which the channel floor can be acquired. A number of protocols, including MACA and IEEE 802.11 [5, 8, 1, 15] use a three or four-way handshake between sender and receiver to avoid collisions. The sender first sends a request-to-send (RTS) packet to the intended receiver; if the RTS is successful the receiver replies with a clear-to-send (CTS) packet, and the sender transmits its data packet only after receiving the CTS. In some protocols, the receiver sends an acknowledgment as part of the MAC protocol after receiving the data packet. This three or four-way handshake amounts to collision detection by the receiver and addresses, at least to some degree, two main problems: (a) The half-duplex nature of single-channel wireless networks, and (b) The hidden-terminal effect [17, 1], which inhibits the transmitter's ability to detect that its intended receiver is receiving multiple transmissions.

In a LAN with a small propagation delay and in which hidden-terminal problems do not occur, collision detection by the transmitter can substantially increase the utilization of the channel; this is the case of CSMA/CD used in Ethernet [12]. However, CSMA/CD requires the sender to sense the channel while it transmits; if the carrier signal has an energy level different than what is expected from the senders transmission, collision is detected, which can happen within one round-trip propagation delay. Unfortunately, a WLAN with a single channel has a half-duplex operation. To cope with this limitation, Lo [11] and Rom [13] have proposed protocols similar to non-persistent CSMA that detect collisions by means of pauses. A station that senses the channel busy defers transmission, a transmitter that senses the channel idle starts transmitting but pauses during transmission and senses the channel. If the channel is sensed idle, the sender completes its transmission; otherwise, the sender continues to transmit for a minimum transmission duration (called the collision detection interval or CDI). Unfortunately, these protocols do not guarantee that a station can sense all collisions [13].

Another CSMA/CA protocol based on the idea of sending a request signal and pausing to sense collisions was proposed and analyzed in [5, 2]. This protocol, however, was designed for LANs in which stations can sense the channel while transmitting.

FAMA-PJ differs from the Lo and Rom protocols in that it enforces floor acquisition and uses jamming from both active and passive stations (i.e., stations involved in sending packets or simply listening).

A station that is just initialized waits two times the maximum channel propagation delay plus the hardware transmit to receive transition time before sending anything over the channel. This permits the station to learn about ongoing packet trains if they exist. A station that is properly initialized (has no packet to send and senses an idle channel) must be in the PASSIVE state. In all states but the PASSIVE state, before transmitting anything a station must listen to the channel for a period of time that is sufficient for the station to receive packets in transit from the station that has the floor. If a station is in the PASSIVE state and detects carrier, it transitions to the REMOTE state; alternatively, if the station receives a packet to send, it sends an RTS and transitions to the RTS state. Note that, although the station sends its RTS after receiving a local data packet, this can occur only after the station has waited the necessary amount of time in another state to learn that the last station having the floor has relinquished the floor. A station that has a packet to send and senses no carrier in the channel for an amount of time longer that the propagation time in the channel plus the transmit to receive turn-around time or the maximum gap allowed between data packets in a packet train transmits an RTS whose duration is longer than twice the maximum propagation time in the channel; the station then pauses to sense the channel. If the station senses the channel to be idle for τ seconds (after the station begins sensing it), the station concludes that its RTS was successful and transmits one or more data packets; otherwise, that station jams the channel for at least one maximum propagation delay.

Jamming of the channel by stations that fail in sending a successful RTS is called *active jamming*; this type of jamming has been proposed in all previous approaches based on pausing and jamming. Active jamming is sufficient to inform all stations that a collision of control packets has occurred if the channel propagation time is longer than the transceiver turn around time ε (the time a packet radio takes to transition from the transmit to listen state). However, as Fig. 1 illustrates, if $\varepsilon \geq \tau$, active jamming is not sufficient to detect collisions. In the example shown in Fig. 1, station A transmits an RTS first, and station B transmits an RTS within τ seconds of A's RTS start. Station B cannot detect collision, because it transitions to the listen state when there is no more carrier produced by A. Station A cannot detect collision, because the carrier produced by B is too weak to be detected by the time A is able to listen to the channel.

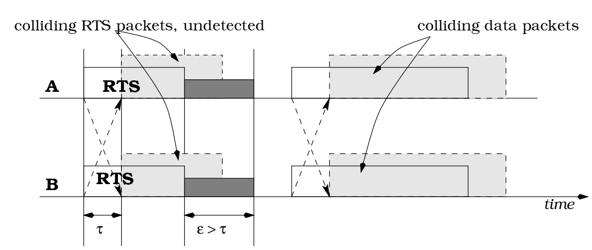

Figure 1: FAMA-PJ active jamming failure under conditions where $\varepsilon > \tau$

To solve the limitations of active jamming, FAMA-PJ uses "passive jamming." Passive jamming can be performed only by stations in the REMOTE state, which prevents stations from jamming one another for indefinite periods of time. When a passive or backed-off station detects carrier and transitions to the REMOTE state it waits for γ seconds. After this time, if it has understood an RTS, it waits another $\varepsilon + \tau$ seconds to begin receiving one or more data packet, or to let another station receive such packets. Otherwise, if no RTS is understood after γ seconds, the station ascertains that there has been a collision in the channel and the station begins "passive jamming" by transmitting a jamming signal for $\varepsilon + 2\tau$ seconds. FAMA-PJ includes active jamming to handle 2-node cases. In a WLAN, the maximum propagation times are on the order of a few microseconds, while ε can be as large as $35\mu s$ [7]; therefore, we make the assumption that $\varepsilon \geq \tau$ throughout the rest of this paper. Figure 2 specifies FAMA-PJ.

The backoff times used in FAMA-PJ are obtained using a

```
Variable Definitions
        CD = Carrier Detected
        T_PROP = Propagation Delay across the channel
        T_RTS = Time required to transmit an RTS packet
        T_PROC = Processing time for carrier detection
        T_TXRX = Hardware transmit to receive transition time
        Burst = Number of packets to send in a burst

Procedure START()
Begin
        Timer ← to (2 × T_PROP) + T_TXRX;
        While(¬CD ∧ Timer not expired) wait;
        If (CD) Then call REMOTE(T_PROP + T_PROC + T_TXRX,0);
        Else call PASSIVE()
End

Procedure PASSIVE()
Begin
        While(¬CD ∧ No Local Packet) wait;
        If (CD) Then call REMOTE(T_PROP + T_PROC + T_TXRX,1);
        Else call RTS(T_PROP)
End

Procedure RTS(T_σ)
Begin
        Transmit RTS Packet;
        Timer ← T_σ + T_TXRX;
        While(¬CD ∧ Timer not expired) wait;
        If (CD)
        Then Begin
                Transmit jamming signal for T_PROP;
                Timer ← T_PROP + T_TXRX;
                While(Timer not expired) wait;
                call BACKOFF();
        End  Else Begin
                call XMIT();
        End;
End

Procedure XMIT()
Begin
        Burst ← maximum burst;
        While (Burst > 0)
        Do Begin
                Transmit Data Packet;
                Burst ← Burst - 1;
        End;
        Timer ← T_PROP + T_TXRX;
        While(Timer not expired) wait;
        If (Local Packet) Then call BACKOFF();
        Else call PASSIVE();
End
```

```
Procedure BACKOFF()
Begin
        If (CD) call REMOTE(T_PROP + T_PROC + T_TXRX,0);
        Else Begin
                Timer ← RANDOM(0,10 × T_RTS);
                While(¬CD ∧ Timer not expired) wait;
                If (CD) Then call REMOTE(T_PROP + T_PROC + T_TXRX,1);
                Else call RTS(T_PROP)
        End
End

Procedure REMOTE(T_σ,flag)
Begin
        Timer ← T_σ;
        While(¬CD ∧ Timer not expired) wait;
        If (Timer Expired)
        Then Begin
                If (Local Packet) Then call BACKOFF();
                Else call PASSIVE();
        End
        Else Begin
                If (flag = 1)
                Then Begin;
                        Timer ← T_RTS;
                        While(Timer not expired) wait;
                        Receive Packet;
                        DO CASE of (received packet type)
                        Begin
                                RTS:
                                        call REMOTE(T_PROP + T_PROC + T_TXRX,0);
                                ERROR:
                                        Transmit jamming signal for (T_TXRX + 2T_PROP);
                                        call REMOTE(T_PROP + T_PROC + T_TXRX,0);
                        End
                End
                Else Begin
                        While (CD) wait;
                        Receive Packet;
                        DO CASE of (received packet type)
                        Begin
                                RTS:
                                        call REMOTE(T_PROP + T_PROC + T_TXRX,0);
                                DATA:
                                        If(Destination ID = Local ID)
                                                Then pass packet to upper layer;
                                        call REMOTE(T_PROP + T_PROC,0);
                                ERROR:
                                        call REMOTE(T_PROP + T_PROC + T_TXRX,0);
                        End
                End
        End
End
```

Figure 2: FAMA-PJ Specification

uniformly distributed random variable distributed over the values from zero to ten times the duration of an RTS transmission. Other backoff strategies can also be used (e.g., see [1]).

3 Floor Assignment in FAMA-PJ

The size of the RTS packets in relation to the data packets is critical to the efficient operation of the protocol. If the size of an RTS packet approaches the size of the data packets, the overhead of the contention period will degrade the performance considerably. Therefore, RTS packets must be kept small as compared to the data packets. RTS packets must also be larger than two times the maximum propagation time (T_{PROP}) across the network. If the RTS packet size is less than two times the propagation time, it is possible for a passive station to hear a clear RTS before others in the network, not jam as required, and allow a data packet to be transmitted that could collide with other traffic on the channel, violating our requirement of collision free data transmissions.

Theorem 1 below shows that, under a number of assumptions, FAMA-PJ ensures that all data packets accepted by the link layer are delivered to the channel within some finite period of time, and that all data packets delivered to the channel reach their proper destination without collisions. The assumptions used are the following:

A0) The maximum end-to-end propagation time in the channel is $\tau < \infty$

A1) A station transmits an RTS that does not collide with other transmission with probability larger than 0.

A2) All stations can hear one another and are within one maximum propagation delay (τ) of all other stations.

A3) All stations execute the FAMA-PJ protocol correctly.

A4) The transmission time of an RTS packet is γ, the transmission time of a data packet is δ, and the processing time is $t_p < \infty$. The hardware transmit to receive transition time is ε, where $\varepsilon \geq \tau$ and $2\tau < \gamma \leq \delta < \infty$.

A5) There are three or more stations in the network

A6) The probability that all stations in the network transmit an RTS simultaneously is 0

Theorem 1 *FAMA-PJ ensures that each new packet, or any of its retransmissions, is sent to the channel within a finite time after it becomes ready for transmission, and that a data packet does not collide with any other transmission provided that $2\tau < \gamma < \infty$.*

Proof:
By this theorem's assumptions, an RTS lasts longer than two times the channel propagation time. Therefore, if an arbitrary station A is able to send an RTS that does not collide with other transmissions, all other stations must detect carrier before A ends transmitting its RTS and must enter the REMOTE state, which forces them to enter a waiting period that lasts longer than $\varepsilon + \tau$ seconds after detecting the end of A's RTS transmission.

Let t_0 be the time when A sends its RTS; station A will be able to send data packets if it senses the channel idle for τ seconds once it transitions to listening mode after sending its RTS; which occurs at time $t_1 = t_0 + \gamma + \varepsilon + \tau$.

If a station $B \neq A$ starts to receive A's RTS at time t_2, it must wait for $\varepsilon + 2\tau$ seconds after receiving A's entire RTS before it can be allowed to send any traffic to the channel. B must receive A's data packet at most τ seconds after A sends it, i.e., at time $t_3 = t_1 + \tau = t_0 + \gamma + \varepsilon + 2\tau$.

Let t_4 denote the time when B is allowed to transmit after not receiving any carrier due to a data packet from A, following As RTS; we have that $t_4 = t_2 + \gamma + \varepsilon + 2\tau$. Because B cannot receive A's RTS in 0 time $t_3 > t_0$; therefore, $t4 > t_0 + \gamma + \varepsilon + 2\tau = t_3$ and B cannot transmit anything to the channel.

This means that once station A transmits an RTS in the clear, it can send a data packet to the channel in the clear. Furthermore, every station in REMOTE state must wait $\varepsilon + \tau$ seconds after the end of any packet received and the station controlling the floor ensures that the gap between any two data packets in a packet train is less than τ. Accordingly, it follows from the above and assumption A1 that, if a station has a data packet to be sent, it delivers the packet to the channel without collisions within a finite time.

Let t_0 be the time when a given passive station PJ receives the first RTS of a series of RTSs that collide in the channel and denote that packet by RTS_0. Any other colliding RTS must be transmitted by a station no later than $t_0 + \tau$; otherwise the station would detect the carrier of RTS_0; furthermore, that RTS must arrive at PJ within τ seconds after it is transmitted. Accordingly, because all propagation delays are positive, it follows that PJ must receive any RTS that collides with RTS_0 no later than $t_0 + 2\tau$.

Because $\gamma > 2\tau$, PJ must detect a collision and jam the channel at time $t_0 + \gamma$, and that jamming persists for $\varepsilon + 2\tau$ seconds. Any station that sends an RTS that collides with RTS_0 must return to the listening mode by time $t_1 = t_0 + \tau + \gamma + \varepsilon$; therefore, given that $t_2 = t_0 + \gamma + \varepsilon + 2\tau > t_1$ is the time when PJ stops jamming the channel, any station that sends an RTS that collides with RTS_0 must detect carrier with PJ's jamming and go the BACKOFF state. It then follows that no station whose RTS collides with other RTSs can send a data packet; therefore, the theorem is true. $\Box$.

4 Approximate Throughput Analysis

To simplify our analysis, we assume the same traffic model first introduced by Kleinrock and Tobagi [10]. The protocols we analyze are non-persistent CSMA, FAMA-PJ, and their slotted counterparts.

4.1 Assumptions and Notations

Using the traffic model in [10], there is an infinite number of stations who constitute a Poisson source sending RTS packets (for the case of FAMA-PJ) or data packets (for the case of CSMA) to the the channel with an aggregate mean generation rate of λ packets.

Each station is assumed to have at most one data block to be sent at any time. In both protocols a station transmits the entire data block as a single packet (which is the case of CSMA) or as multiple packets (which is the case of FAMA-PJ). The hardware is assumed to require a fixed turn-around time of ε seconds to transition from transmit to receive, for any given transmission to the channel. The average size of a data block is δ seconds. RTS packets are of size γ seconds, and the maximum end-to-end propagation delay of the channel is τ seconds. Collisions (e.g., RTS packets in FAMA-PJ, data packets in CSMA) can occur in the channel, and we assume that, when a station has to retransmit a packet it does so after a random retransmission delay that, on the average, is much larger than δ. The average channel utilization is given by [16]

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}}. \quad (1)$$

where $\overline{B}$ is the expected duration of a busy period, defined to be a period of time during which the channel is being utilized; $\overline{I}$ is the expected duration of an idle period, defined as the time interval between two consecutive busy periods; and $\overline{U}$ is the time during a busy period that the channel is used for transmitting user data successfully.

The channel is assumed to introduce no errors, so packet collisions are the only source of errors, and stations detect such collisions perfectly. To further simplify the problem, we assume that every station can listen to the transmissions of any other station, that two or more transmissions that overlap in time in the channel must all be retransmitted, and that a packet propagates to all stations in exactly τ seconds [16]. The later assumption provides a lower bound on the performance of the protocols we analyze.

The turn around time ε for a station to transition from transmit to receive or receive to transmit is assumed to be greater than or equal to the propagation delay τ.

Of course, this model is only a rough approximation of the real case, in which a finite number of stations access the same channel, some stations may not be able to hear some other stations' transmissions, stations can queue multiple packets for transmission, and the stations' transmissions and retransmissions (of RTS or data packets) are highly correlated because of the relationships between them (i.e., a failed RTS is followed by another RTS within a bounded time, and a singular data packet or packet train is always preceded by a successful RTS). However, our analysis provides additional insight on the performance of MAC protocols for WLANs based on collision detection at the sender as well as passive receivers, which has not been addressed in recent protocol proposals, and the impact of channel speed and propagation delay on the floor acquisition technique. Our analysis favors CSMA in that we assume that the applications sending data to the channel can efficiently use data packets much larger than the size of an RTS.

4.2 FAMA-PJ

Figure 4 shows the transmission periods for the FAMA-PJ protocol. In FAMA-PJ, a station transmits an RTS packet and then listens for τ seconds. If the channel remains clear during this period, the station transmits the data packet. Otherwise, it transmits a jamming signal of τ seconds in length. Additionally, all passive stations (all stations either in the PASSIVE or BACKOFF state) listen to the signal, and after γ seconds from carrier detection they make a determination the the RTS is clear, or there has been a collision. It the RTS is clear, the RTS is processed normally and the station waits for the data impending data packet to arrive. If a collision has been detected the station begins transmission of a jamming signal $\varepsilon + 2\tau$ seconds in length. After any transmission period, the FAMA-PJ specification enforces a τ second long waiting time before stations transition to the PASSIVE or BACKOFF state.

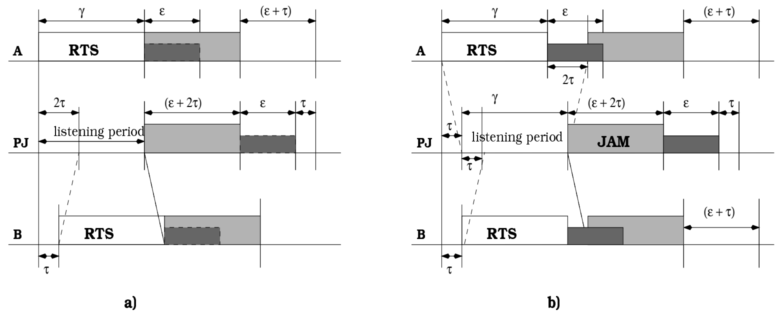

Figure 3: FAMA-PJ passive jamming periods:
a) Stations A and PJ are next to each other.
b) Stations A and PJ are τ seconds apart.

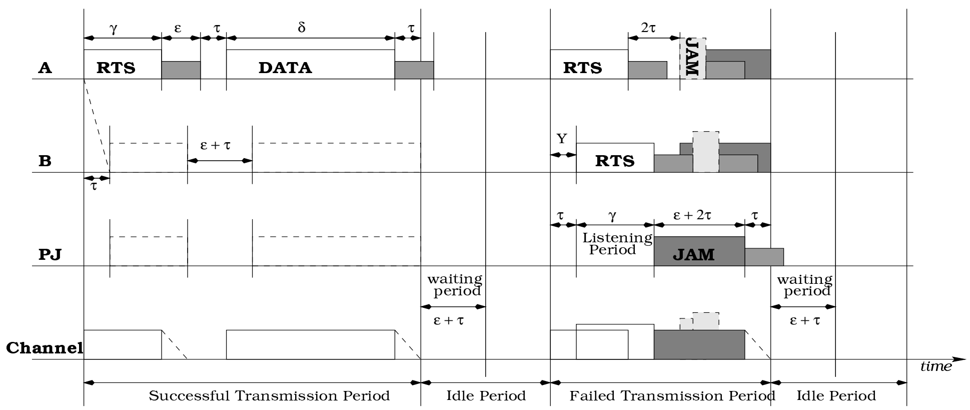

Figure 4: FAMA-PJ transmission periods

Theorem 2 *The throughput of FAMA-PJ is given by*

$$S = \frac{\delta}{\delta - 2\tau + e^{\lambda\tau}(\gamma + 5\tau + 2\varepsilon + \frac{1}{\lambda})} \tag{2}$$

Proof:
A successful transmission period (T) consists of an RTS packet followed by the hardware transmittoreceive transition (ε seconds), a listening period of τ seconds, and a data packet followed by the τ second propagation delay across the channel; therefore,

$$T = \delta + \gamma + 2\tau + \varepsilon \tag{3}$$

An unsuccessful transmission period (T_{FAIL}) consists of an RTS payload (γ seconds in length), a τ second propagation delay to the passive jammer, a jamming signal of $\varepsilon + 2\tau$ seconds, and a final propagation delay of τ seconds across the channel. Therefore, the duration of the average failed transmission period is

$$T_{FAIL} = \gamma + 4\tau + \varepsilon \tag{4}$$

The probability P_S of a successful transmission is the probability that no other packet arrives during a propagation delay, i.e., $e^{-\lambda\tau}$.

The FAMA-PJ specification enforces a waiting period of $\tau + \varepsilon$ seconds after any given busy period, which is in turn followed by an idle period. Because of this, a busy period is made up of either one successful or unsuccessful transmission period; therefore,

$$\begin{aligned}\overline{B} &= P_S T + (1 - P_S)T_{FAIL} \\ &= e^{-\lambda\tau}(\delta - 2\tau) + \gamma + 4\tau + \varepsilon\end{aligned}$$

$\overline{U}$ equals $\delta P_S = \delta e^{-\lambda\tau}$, and $\overline{I}$ is simply the average interarrival time of RTSs into the channel, plus the enforced waiting time of $\tau + \varepsilon$ seconds, i.e., $(1/\lambda) + \tau + \varepsilon$.

Substituting $\overline{U}, \overline{B}, \overline{I}$ into Eq. (1) we obtain Eq. (2). □.

4.3 Slotted FAMA-PJ

We consider Slotted FAMA-PJ with the assumptions that the slot size equals the propagation delay τ, the length of the hardware transmit to receive transition time ε and the duration of an RTS and DATA packets are exact multiples of τ. Stations may only start transmissions at slot boundaries. Figure 5 shows the transmission periods possible for Slotted FAMA-PJ.

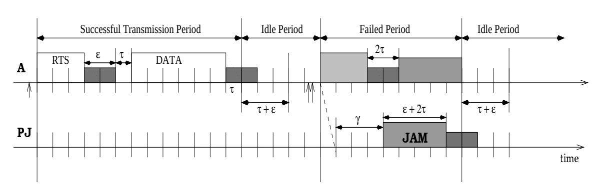

Figure 5: Slotted FAMA-PJ transmission periods

Theorem 3 *The throughput of Slotted FAMA-PJ is given by*

$$S = \frac{\delta}{\delta - 2\tau + \left[\frac{\gamma+6\tau+2\varepsilon-e^{-\lambda\tau}(\gamma+5\tau+2\varepsilon)}{\lambda\tau e^{-\lambda\tau}}\right]} \quad (5)$$

A successful transmission period for slotted FAMA-PJ consists of one RTS packet followed by the hardware transmit to receive transition time (ε seconds in length) along with one slot (τ seconds in length) to listen for other transmissions, and one DATA packet followed by one slot for final propagation delay. This is the same as in unslotted FAMA-PJ, and T is given in Eq. (3).

An unsuccessful period consists of one propagation slot for the colliding packets to reach the passive jammer (PJ), the length of an RTS packet (γ) for PJ to determine the collision has taken place, a jamming signal of $\varepsilon + 2\tau$ seconds duration, with one slot for final propagation. The failed period is therefore,

$$T_{FAIL} = \gamma + 4\tau + \varepsilon \quad (6)$$

A busy period consists of either one successful, or one unsuccessful transmission period. This is because a waiting period is enforced by the FAMA-PJ specification after any transmission period, followed by an idle period. The probability P_S of a successful transmission is the probability of having only one arrival in a busy slot, i.e.,

$$P_S = \frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})} \quad (7)$$

The average length of a busy period ($\overline{B}$) is then

$$\begin{aligned}\overline{B} &= P_S T + (1-P_S)T_{FAIL} \\ &= \left[\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}\right](\delta - 2\tau) + \gamma + 4\tau + \varepsilon \end{aligned} \quad (8)$$

The utilization of the channel, $\overline{U}$, is the data portion of a successful transmission period. Therefore, with probability P_S a transmission is successful and the data portion of such a period is δ, we obtain

$$\overline{U} = \delta P_S = \delta\left[\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}\right] \quad (9)$$

The idle period consists of consecutive empty slots preceded by an enforced waiting period of $\tau + \varepsilon$ seconds in length, as defined by the FAMA-PJ specification. The number of consecutive idle slots has a geometric distribution whose mean is the same as that derived for slotted non-persistent CSMA [10, 14] and is equal to $1/(1-e^{-\lambda\tau})$. The average idle period is then equal to the average number of consecutive empty slots plus the $\tau+\varepsilon$ second enforced waiting period. Therefore,

$$\overline{I} = \frac{\tau}{(1-e^{-\lambda\tau})} + \tau + \varepsilon \quad (10)$$

Substituting $\overline{U}$, $\overline{B}$ and $\overline{I}$ into Eq.(1) we obtain Eq.(5). □.

4.4 Performance Comparison

To facilitate the comparison of the various protocols, we normalize the results obtained for S by making $\delta = 1$ and introducing the following variables

$a = \frac{\tau}{\delta}$ (normalized propagation delay)

$b = \frac{\gamma}{\delta}$ (normalized control packets)

$c = \frac{\varepsilon}{\delta}$ (normalized transmit to receive turn around time)

$G = \lambda \times \delta$ (Offered Load, normalized to data packets)

Table 1 lists the normalized throughput equations for non-persistent CSMA and FAMA-PJ. For the case of non-persistent CSMA, we assume the existence of an additional perfect channel for the transmission of acknowledgments to data packets; therefore, the throughput shown for CSMA is an upper bound. For the case of FAMA-PJ, because we assume that errors are due only to packet collisions and data packets are always transmitted in the clear, there is no need for acknowledgments to data packets under the assumption of no channel errors. However, because propagation delays and acknowledgments are much smaller than data packets, the effect of acknowledgments would have a negligible effect on FAMA-PJ throughput.

We have compared the operation of the FAMA-PJ protocol with non-persistent CSMA under a variety of possible scenarios. We compare operation in a high speed network (1 Mb/s), and using data packets of 500, 1000 and 1500 bytes (as might be seen in normal Ethernet traffic). We assume a network with a maximum diameter of 1000 feet, which gives us a propagation delay of approximately 1μs. The RTS packets are 20 bytes long to accommodate the use of IP addresses for destination and source information, a CRC, and framing bytes. The transmit to receive turnaround time is assumed to be 20μs, similar to the recommendations of the IEEE 802.11 committee [7]. Table 2 shows the values of a, b and c used to approximate the results for the comparison. Figure 6 shows the throughput (S) verses the offered load (G) for the FAMA protocols under these conditions.

1Mbit/s Network	a	b	c
500 Byte data packets	0.00025	0.040	0.0050
1000 Byte data packets	0.000125	0.020	0.0025
1500 Byte data packets	0.000083	0.0133	0.00167

Table 2: FAMA-PJ protocol variables

Our results show the viability of using a collision detection mechanism at the sender and passive receivers along with carrier sensing as a floor acquisition scheme. Slotting adds little performance improvement over the basic FAMA-PJ protocol.

In high-speed channels, it is clear that a larger throughput can be obtained with a larger ratio of δ/γ. Because transmitting very long data packets may not be appropriate in some applications using the network, floor acquisition, i.e., allowing a station to send packet bursts in the clear after a successful RTS, becomes very attractive. Figure 7 further illustrates the importance of floor acquisition in the performance of the network for applications requiring either the transfer of large amounts of data (e.g., video transmissions) or the distribution of different information to different destinations. Again, a large ratio of δ to γ gives a high throughput in FAMA-PJ. For applications able to use larger packet trains, FAMA-PJ in a high-speed channel is more effective than non-persistent CSMA.

Protocol	*Unslotted version*	*Slotted Version*
CSMA [10]	$\frac{Ge^{-aG}}{G(1+2a)+e^{-aG}}$	$\frac{aGe^{-aG}}{1+a-e^{-aG}}$
FAMA-PJ	$\frac{1}{1-2a+e^{aG}(b+5a+2c+\frac{1}{G})}$	$\frac{1}{1-2a+\left[\frac{b+6a+2c-e^{-aG}(b+5a+2c)}{aGe^{-aG}}\right]}$

Table 1: Throughput Equations for CSMA and FAMA-PJ protocols

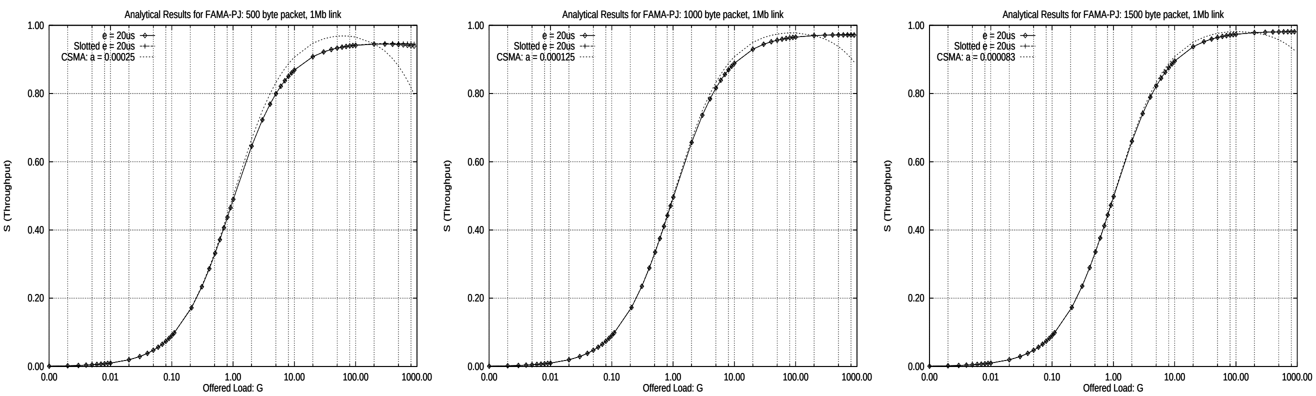

Figure 6: Analytical performance comparison of the FAMA-PJ protocol in a high speed network.

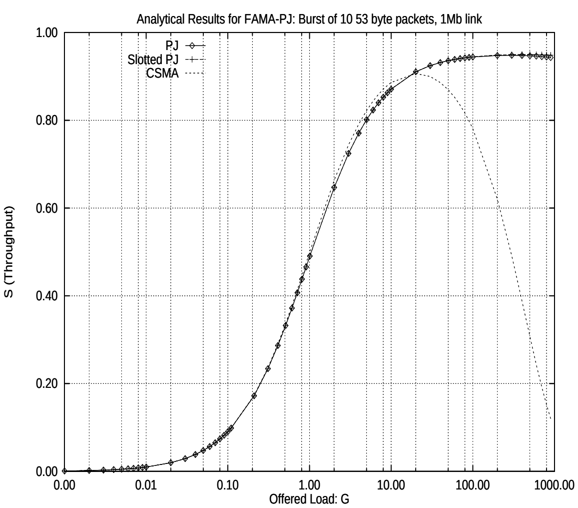

Figure 7: Throughput of FAMA-PJ protocols using a 10 packet train in a high-speed network.

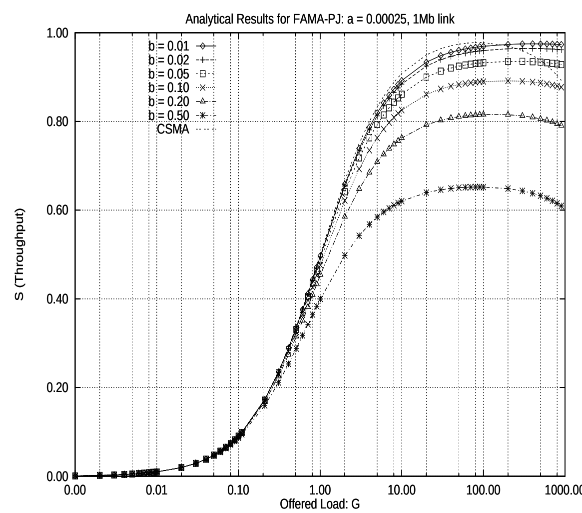

Figure 8: Throughput of FAMA-PJ versus b in a high speed network.

5 Average Delay

To determine the average delay, we consider the transitions a station makes upon receiving a data packet, the probability of such transitions, and the related average delays incurred until the data packet is successfully delivered. Given the memoryless properties of the interarrival times of packets in the channel, we model the average delay experienced by a data packet as a Markov process; a state of this process corresponds to a state in which a station with a packet to deliver is. Our model consists of four states, ARRIVE, BACKOFF, ATTEMPT and COMPLETE. Figure 9 shows the individual states and their respective possible transitions along with the probabilities and delays associated with each of them.

The ARRIVE state is the entry point to the system for a station receiving a new packet to deliver. On the arrival of the data packet, the station finds the channel busy with

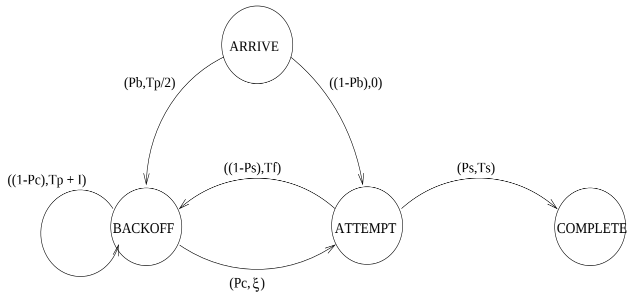

Figure 9: Markov chain defining FAMA-PJ delay characteristics.

probability P_B and incur a partial transmission period. Because the arrival process is Poisson, arrival times during any given time interval are independent and uniformly distributed [18]. Therefore, on the average, the partial transmission period the station experiences is $T_P/2$, where T_P is the duration of an average transmission period. The station will then transition to the BACKOFF state.

Alternatively, with probability $(1-P_B)$, the channel is clear when the station receives a packet to deliver, and the station incurs no delay and transitions to the ATTEMPT state. In the ATTEMPT state a station attempts to gain the floor. With probability P_S the station is successful and the data packet is delivered successfully, incurring a delay of one successful transmission period, denoted by T_S. With probability $(1-P_S)$ the station fails to acquire the floor, incurs a delay of a failed transmission period, denoted by T_F, and transitions to the BACKOFF state.

The BACKOFF state represents the stations random waiting periods before attempting to acquire the channel again. The average waiting period is ξ seconds. With probability P_C a station completes its waiting period and transitions to the ATTEMPT state and incurs a ξ-second delay. Otherwise, with probability $(1-P_C)$, some other arrival to the channel occurs first and causes the station to be delayed one average transmission period, plus the average idle time, and be returned to the BACKOFF state.

The COMPLETE state represents the completed successful delivery of the data packet by the station, and ends the process.

To calculate the average delay we solve the system of equations implied by the graph in Figure 9. Let $\overline{D}$ equal the expected delay incurred by a station with a new packet received at the ARRIVED state until it is successfully delivered at the COMPLETE state. Let $E(A)$ equal the expected delay incurred on each visit by the station to the ATTEMPT state, and let $E(B)$ equal the expected delay incurred on each visit to the BACKOFF state. From the graph in Figure 9 we obtain

$$\overline{D} = P_B\left[\frac{T_P}{2} + E(B)\right] + (1-P_B)\left[0 + E(A)\right] \quad (11)$$

$$E(B) = P_C\left[\xi + E(A)\right] + (1-P_C)\left[T_P + \overline{I} + E(B)\right] \quad (12)$$

$$E(A) = P_S \cdot T_S + (1-P_S)\left[T_F + E(B)\right] \quad (13)$$

Solving for $E(B)$ we obtain

$$E(B) = \frac{T_P + \overline{I}}{P_C P_S} + \frac{\xi + T_F - T_P - \overline{I}}{P_S} + T_S - T_F \quad (14)$$

Substituting Eqs. (13) and (14) into Eq. (12) we obtain the formula for the expected delay

$$\overline{D} = T_P + T_S - T_F - \xi - \overline{I} + P_B\left[\xi - \overline{I} - \frac{T_P}{2}\right] + \frac{\xi + T_F - T_P - \overline{I}}{P_S} + \frac{(P_B - 1)\left(T_P + \overline{I}\right)}{P_C} + \frac{T_P + \overline{I}}{P_C P_S} \quad (15)$$

Eq.(15) may be used for both FAMA-PJ and Slotted FAMA-PJ by a simple substitution of the appropriate values for each protocol.

5.1 FAMA-PJ

Some of the parameters for Eq.(15) have been derived previously in Section 4. $T_S = T$, is given in Eq.(3). The probability of success, P_S, is derived in the proof of Theorem 2, along with $\overline{I}$ and $\overline{B}$ (given in Eq.(5)).

The probability of finding the channel busy P_B is equal to the average busy period divided by the average cycle time

$$P_B = \frac{\overline{B}}{(\overline{B} + \overline{I})} = \frac{e^{-\lambda\tau}(\delta - 2\tau) + \gamma + 4\tau + \varepsilon}{e^{-\lambda\tau}(\delta - 2\tau) + \gamma + 5\tau + 2\varepsilon + \frac{1}{\lambda}} \quad (16)$$

The probability of completing a backoff waiting period P_C is equivalent to having no other arrivals during the waiting period. The length of an average waiting period is ξ seconds, therefore

$$P_C = e^{-\lambda\xi} \quad (17)$$

The delay incurred by a station failing at the attempt to acquire the floor is the length of an RTS plus the length of the jamming period. If the station is the first station in the failed period it will incur a delay of $\gamma + \varepsilon + 4\tau$, if it is the last station in the failed period it will incur a delay of $\gamma + \varepsilon + 4\tau - \overline{Y}$, where $\overline{Y}$ is the average time of the last arrival in a failed period. The average delay incurred by all stations in a failed period is therefore

$$T_F = \gamma + \varepsilon + 4\tau - \frac{\overline{Y}}{2} \quad (18)$$

As in non-persistent CSMA [10], The cumulative distribution function for Y is the probability that no arrivals occur in the interval of length $\tau - y$ and equals $F_Y(y) = e^{-\lambda(\tau - y)}$[10] (where $y \le \tau$); therefore the expected value of Y is [10]

$$\overline{Y} = \tau - \frac{(1 - e^{-\tau\lambda})}{\lambda}. \quad (19)$$

Substituting Eq.(19) in Eq. (18) we obtain

$$T_F = \gamma + \varepsilon + \frac{7}{2}\tau + \frac{(1 - e^{-\lambda\tau})}{2\lambda} \quad (20)$$

The average transmission period T_P is equivalent to an average busy period, there $T_P = \overline{B}$ and is given in Eq.(5).

Substituting these values into Eq.(15) for FAMA-PJ we obtain

$$\overline{D}_{PJ} = e^{-\lambda\tau}(\delta - 2\tau) + \delta + \gamma + \frac{3}{2}\tau + \frac{(1 + e^{-\lambda\tau})}{2\lambda} - \xi + P_B\left(\xi - \frac{1}{\lambda} - \frac{e^{-\lambda\tau}(\gamma + 6\tau + 3\varepsilon)}{2}\right)$$

$$+\frac{e^{-\lambda\tau}(2\tau-\delta)-\frac{3}{2}\tau-\varepsilon+\xi-\frac{(1+e^{-\lambda\tau})}{2\lambda}}{e^{-\lambda\tau}}$$
$$+\frac{(P_B-1)\left[e^{-\lambda\tau}(\delta-2\tau)+\gamma+5\tau+2\varepsilon+\frac{1}{\lambda}\right]}{e^{-\lambda\xi}}$$
$$+\frac{e^{-\lambda\tau}(\delta-2\tau)+\gamma+5\tau+2\varepsilon+\frac{1}{\lambda}}{e^{-\lambda(\tau+\xi)}} \qquad (21)$$

5.2 Slotted FAMA-PJ

As for FAMA-PJ many of the values needed for Eq.(15) have already been determined in Section 4. $T_S = T$ and is given in Eq.(3). $T_P = \overline{B}$ given in Eq.(8) and P_S is given in Eq.(7). Also, the value used for ξ, the average backoff timer, is an exact multiple of τ.

The probability P_B of finding the channel busy on arrival is found from $\overline{B}$ and $\overline{I}$, given in Eqs.(8) and (10), and equals

$$P_B = \frac{\overline{B}}{(\overline{B}+\overline{I})} = \frac{\left[\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}\right](\delta-2\tau)+\gamma+4\tau+\varepsilon}{\left[\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}\right](\delta-2\tau)+\gamma+5\tau+2\varepsilon+\frac{\tau}{(1-e^{-\lambda\tau})}} \qquad (22)$$

The probability P_C of the backoff timer expiring is equal to the probability of no arrivals during this period. This is the same as for FAMA-PJ and is given in Eq.(17).

In a failed attempt to gain the floor a station incurs the time to transmit the RTS, a 2τ propagation delay before the jamming signal arrives, and the length of the jamming signal. Therefore, a failed attempt to transmit, $T_F = \gamma+\varepsilon+4\tau$, Substituting these into Eq.(15) for FAMA-PJ we obtain

$$\overline{D}_{SPJ} =$$
$$\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}(\delta-2\tau)+\delta+\gamma+3\tau-\xi-\frac{\tau}{(1-e^{-\lambda\tau})}$$
$$+P_B\left[\xi-\frac{\tau}{(1-e^{-\lambda\tau})}-\frac{\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}(\delta-2\tau)+\gamma+6\tau+3\varepsilon}{2}\right]$$
$$+\frac{\xi-\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}(\delta-2\tau)-\frac{\tau}{(1-e^{-\lambda\tau})}-\tau-\varepsilon}{\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}}$$
$$+\frac{(P_B-1)\left[\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}(\delta-2\tau)+\gamma+5\tau+2\varepsilon+\frac{\tau}{(1-e^{-\lambda\tau})}\right]}{e^{-\lambda\xi}}$$
$$+\frac{\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}(\delta-2\tau)+\gamma+5\tau+2\varepsilon+\frac{\tau}{(1-e^{-\lambda\tau})}}{e^{-\lambda\xi}\frac{\lambda\tau e^{-\lambda\tau}}{(1-e^{-\lambda\tau})}} \qquad (23)$$

5.3 Throughput-Delay Characteristics

Figure 10 compares the delays obtained in FAMA-PJ and non-persistent CSMA. The graph uses $\tau = 0.0001$, $\gamma = 0.02$, $\varepsilon = 0.002$ and $\xi = 5 \times \gamma$ (the size of our RTS packet) for FAMA-PJ, and $\xi = T$ (the size of a data packet) for non-persistent CSMA. FAMA-PJ shows to be more stable than non-persistent CSMA, maintaining a high throughput during periods of high traffic conditions. Our results also indicate that the addition of collision detection by the sender does not impact the delay characteristics appreciably. The delay for both FAMA-PJ and slotted FAMA-PJ are never worse than that of non-persistent CSMA under low-traffic conditions, and perform much better than non-persistent CSMA under high-traffic conditions. This is an important finding, as it shows that the cost of providing a more stable channel access strategy that eliminates collisions of data packets dynamically using collision of control packets by the sender is negligible compared to using non-persistent CSMA.

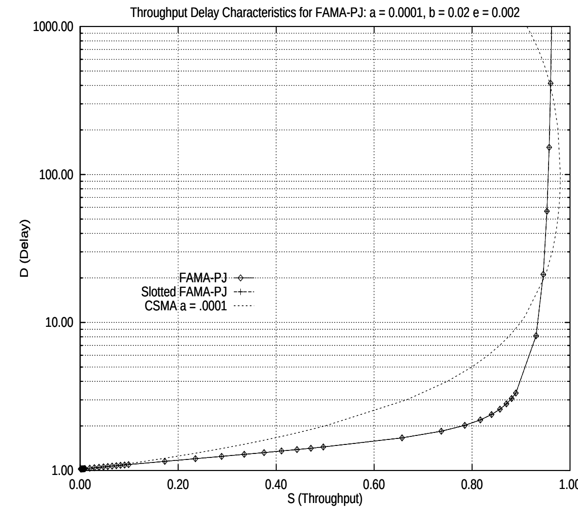

Figure 10: Delay performance of FAMA-PJ and slotted FAMA-PJ.

6 Conclusions

We have specified and analyzed the floor acquisition multiple access using pauses and jamming (FAMA-PJ) protocol. We have shown that the protocol guarantees that a station will be able to transmit one or more data packets with no collision from other stations transmissions. We have also provided an analysis of the average delay characteristics of FAMA-PJ and compared it with non-persistent CSMA. Our results show that the delay costs of providing floor acquisition using collision detection in a WLAN is the same or better than that for non-persistent CSMA. In addition, our results indicate that a floor acquisition strategy can be more stable than non-persistent CSMA. The results also show slotting provides little improvement in throughput over the unslotted version of the protocol in a high-speed WLAN.

Our work continues to analyze the behavior of the FAMA-PJ protocol in multi-hop WLANs and to identify, develop and analyze additional variants of floor acquisition strategies.

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